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CRYOGENIC OPTICAL PERFORMANCE VERIFICATION METHODS FOR OPTICAL COMPONENTS, COATINGS AND OPTICAL SYSTEMS.

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I. INTRODUCTION

NOVA-ASTRON has delivered a suite of cryogenic astronomical instruments for large ground based telescopes as well as space missions. The instruments include polarimeters, spectrometers, cameras and interferometers, mostly operating at infrared. Several methods have been developed to verify or measure, under cryogenic conditions, the performance of optical components, coatings and complete optical systems.

The test and verification setups presented in this paper include wave front error measurements, alignment inspection, spectral measurements, material properties determination and varying gravity orientation capabilities (gravity load vector). The measurement principles are explained, together with the most important error contributions and the achieved accuracies.

II. CRYOGENIC WAVE FRONT MEASUREMENTS

A. Measurement Principles and Setup

A Fizeau Interferometer (with 150 mm beam) is combined with a cryostat to measure interferometric wave front errors at temperatures down to 20K. The test cryostat can hold units up to 200 x 200 x 400 mm and is mostly used to test single components and smaller assemblies. It has a large optical window (Ø=180mm) that allows interferometric measurements. Cooling is provided by a closed cycle cooler. Multi-layer insulation, a thermal radiation sheet and a vacuum environment <$1e^{-5}$ mBar are used for thermal insulation. The temperature of the test sample can be logged with a suite of temperature sensors: Pt100, Pt1000, Si-diode and optional optical FBG sensors. Each temperature sensor has specific properties in temperature range and accuracy.


Fig. 1. Left: Large aperture WYKO 6000 laser interferometer for wave front testing with a beam diameter of 150mm. Right: Cryostat with 150mm clear aperture window on the left (partly obscured by thermal radiation sheet in this setup). The object being studied is in the center of the cryostat and the cold head with closed cycle is cooler on the right.

Described below is a measurement of the influence of cryogenic temperatures on an optical transmission element. Light from the interferometer enters the cryostat via an optically flat entrance window. A differential measurement is required to achieve a high accuracy in wave front error. First, a reference mirror is measured without sample. This is the reference measurement (Figure 2). Then a sample with a small wedge is mounted in the cryostat. The wedge prevents Fabry-Pérot interference between the front and back surface of the sample (in fact the entrance window is also wedged for this reason). Because of the wedge it is possible to measure solely the reflection of the front surface of the sample, the reflection of the back surface of the sample and the sample in transmission, by simply rotating the entire cryostat (including test sample) over a small angle. The reference mirror is a low-CTE fused silica mirror that is oversized, thick, solid and mounted with the goal to prevent the appearance of WFE errors in the mirror at any temperature. The wave front error is calculated as follows:

Sample Front Surface WFE = ('Sample Front Surface Reflection' _ 'Reference Measurement') (1)

Sample Back Surface WFE = ('Sample Back Surface Reflection' _ 'Reference Measurement') / n (2)

Sample Transmission WFE = ('Sample Transmission Measurement' _ 'Reference Measurement') / 2 (3)

In order to determine the influence of temperature on the setup, all measurements are done at both room temperature and cryogenic temperatures, as this WFE difference is our primary interest. The obtained room temperature WFE and cryogenic WFE are simply subtracted.

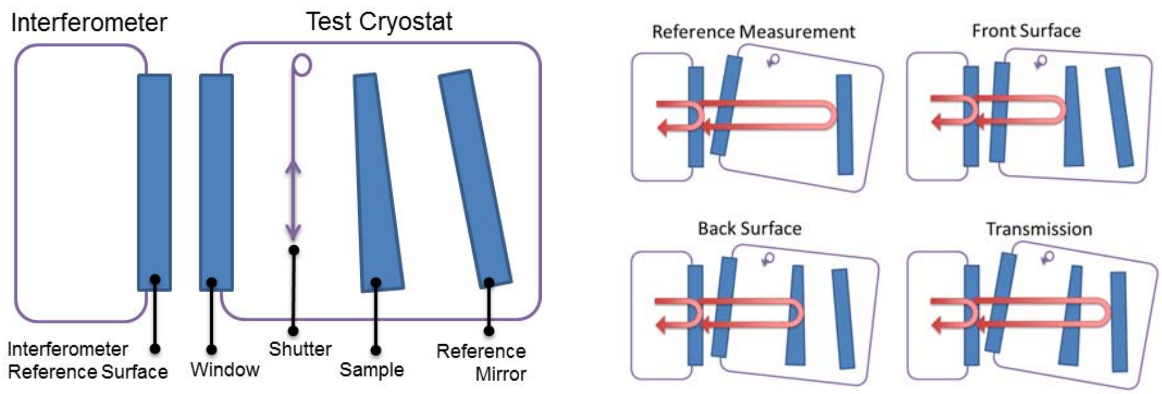


Fig. 2. Left: Overview of the setup with the most important components in the interferometer and test cryostat. Right: First a reference measurement is taken without sample. After loading the sample, the reflection of the front surface, the reflection of the back surface, and the transmission of the sample can be measured alternatively in a single cool down run by a slight rotation of the test cryostat.

B. Error Contributions and Achieved Accuracies

Wave front error contributions are expected from the following sources (the effects are numbered):

1. Temperature induced WFE changes in the sample e.g. caused by its mount (primary interest).
2. Thermal gradients over the vacuum window (window is exposed to cold when the shutter opens).
3. Thermal gradients over the sample (sample is exposed to room temperature window when shutter opens).
4. Deformation of the vacuum window due to pressure difference.
5. The wave front error of the reference mirror (applicable for front and back surface measurements).
6. Deformation of the reference mirror due to cool down (only applicable for transmission measurements).
7. Static WFE imperfections in the sample (front surface WFE, back surface WFE, material imperfections).
8. Movement of optical components (window, sample and reference mirror) with respect to interferometer.
9. Accuracy and reproducibility of the WFE measurement.

Discussion effect #1. This temperature induced WFE effects in the sample is the measurement objective.

#2+#3. In order to gain insight in the effect, drift measurements are taken over a longer time interval of 10 minutes after opening the Shutter. From an analysis of the Zernike coefficients in the measured WFE, it appears that mainly the defocus (power) term changes. This is due to thermal lensing of the cryostat window, which sees besides a pressure gradient, a large temperature gradient, from room temperature (outside the cavity) to cryogenic temperatures (inside the cavity) after opening the shutter. At the same time the cold sample 'sees' the hot cryostat window. Results of the drift measurement are shown in figure 3 and amount to ~7nm per minute in the WFE power term, across the whole aperture. To minimize the thermal disturbances of the blank by the cryostat, all measurements must be taken immediately after opening the shutter, and finished within 60 seconds. The variation in average power term from one measurement to the next measurement are then expected to be a fraction of this 7nm/minute drift term: <3nm. However this also depends on the stabilization time after reaching the required temperature (which is partly schedule driven), the time needed for alignment (the shutter must be opened for interferometer alignment) and the time the shutter was closed between alignment and the start of the measurement). In practice we see variations of ±20nm in this WFE power term. For some applications we are not interested in the power term, and this term can be omitted.

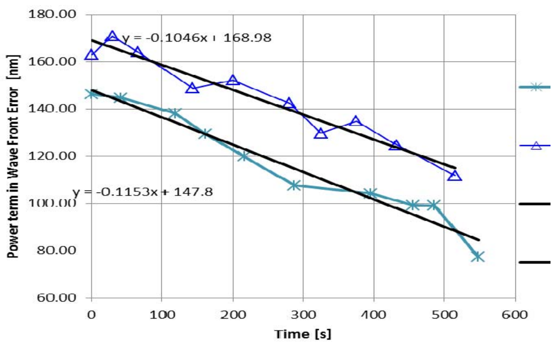
#4. The effect of the pressure difference on the vacuum window is virtually canceled by also taking the room temperature measurements in a evacuated cryostat. Temperature induced variations in mechanical properties of the window can result in WFR effects of a few nm RMS.

#5+#6. The wave front error of the reference mirror was measured to be <30nm P-V and <4nm RMS over the full interferometer aperture. For the Sample front side and back side reflection measurements the WFE of the reference mirror impacts the results at a level of <4 nm RMS. The transmission results are impacted by temperature induced effects of the reference mirror. These effects are estimated to be also <4nm RMS.

#7. Static WFE imperfections of the sample are in principle removed by the differential measurement method (subtraction of room temperature and cryogenic measurements). However, residuals can occur if the position of the sample changes between the room temperature and cryogenic measurements (due to e.g. repositioning or CTE effects). If the static WFE errors of the sample are low order Zernike terms, the differential measurement method virtually cancels this WFE. Local imperfections and edge effects can however be amplified (up to a factor 2) if the lateral shift between the warm and cold measurements is larger than the size of these imperfections. Assuming lateral shifts <3% of the diameter and only low order WFE terms in the sample to a value of <150nm P-V, these effects can amount to <20nm WFE P-V.

#8. Optical components (window, sample and reference mirror) appear to move with respect to the interferometer due to the rotation of the cryostat. Part of the wave front error of these components is no longer canceled in the differential measurement, similar to the explanation of item 2. These effects can amount to <20nm WFE.

#9. Reproducibility errors in the WFE measurement are estimated to be 15nm P-V and 4nm RMS.



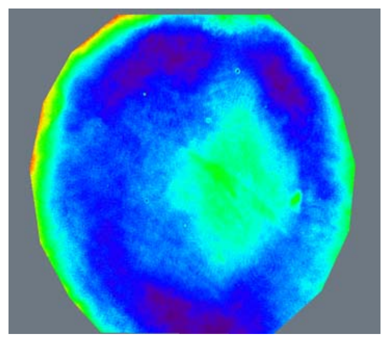


Fig. 3. Left: Drift for two different cold measurements after opening the Shuter (t=0s) measured during 600 seconds. Right: Reference mirror Wave front error over the full aperture (150mm): P-V 29.3 nm, RMS 3.8 nm.

The full field WFE measurement accuracy is 11nm RMS and 38nm P-V if we can omit the dominant power terms, otherwise an accuracy of 24nm RMS and 78nm P-V is achievable. See table 1. There are plans to improve the performance of the setup. The window will be placed on an extension tube with a number of baffles. This reduces effects #2, #3 and #4 as the view factor of the window towards the cold environment is reduced. Alignment of the Sample with the spectrometer reduces effect #7. Placing the sample and reference mirror on rotation stages reduces effect #8. Taking the shape of the reference mirror into account reduces effects #5 & #6. Averaging multiple measurements reduces effect #9. It is expected that the WFE accuracy can be improved to 6nm RMS and 21nm P-V, or even 3nm RMS and 11nm P-V when omitting dominant power terms.

Table 1. Error budget estimation for the measurement accuracy of WFE measurements (full field Ø150mm).

Description	WFE P-V Transmission [nm]	WFE P-V Reflection [nm]	WFE RMS Trans.+Refl. [nm]	Possible Improved WFE P-V [nm]	Possible Improved WFE RMS [nm]
Effect #4	7	7	2	3	0.5
Effect #5		30	4	5	1
Effect #6	20		4	5	1
Effect #7	20	20	7	4	1
Effect #8	20	20	7	6	2
Effect #9	15	15	4	5	2
Total WFE accuracy excluding power term	**38**	**44**	**11**	**11**	**3**
Effect #2 & #3 (power term)	30	30	10	10	3
Total WFE accuracy incl. dominant power term	**68**	**74**	**21**	**21**	**6**

III. CRYOGENIC ALIGNMENT INSPECTION AT VARYING GRAVITY ORIENTATION

Spectrometers, mounted to the Cassegrain focus of a ground based telescope, suffer from flexure due to the varying direction of gravity with respect to the optical bench. This can result in drifts or wanders in the spectral performance and this behavior must be characterized [1]. For space missions it is difficult to measure the performance of an instrument at zero gravity before launch. However, if the performance of the system is acceptable and stable at different gravity orientations (e.g. +1g and -1g), then it is assumed that the performance is approved at 0g [2].

A. Measurement Principles and Setup

An adjustable gravity orientation system (Telescope movement simulator) can position an optical bench (in a cryostat) in any orientation with respect to gravity. A test cryostat can be attached to the telescope movement simulator, and hold optical devices up to round 700 mm and 700 mm of height, and reaches temperatures down to 12K. The cryostat has numerous optical ports and it is possible to extend the cryostat size in height if needed.

Fig. 4. Left: Telescope movement simulator, capable to position a large cryostat in any orientation with respect to gravity. Right: Large test cryostat with vacuum and cryogenic equipment.

A number of techniques are available to verify the alignment of the optical system and measure the performance. This includes alignment telescopes, autocollimators, laser beams, Shack-Hartmann sensor, (customized) Bahtinov masks and position sensors. The difficulty with this kind of measurement setup is that the measurement system itself can also suffer from flexures due to the varying gravity orientation. Therefore it is preferred to directly measure the performance of the optical system and to use an optical fiber to interface with a stable illumination source, e.g. spectral lamps or lasers. Phase diversity or intra- and extra-focal measurements can provide additional information on the position and shape of optical components.

B. Error Contributions and Achieved Accuracies

The DA400 Autocollimator can measure the tip and tilt of flat reflective components with an accuracy up to 0.00006 degrees ((+/-0.2 arcsec) depending on the required range.

The alignment telescope can measure the position and repeatability of mechanisms with an accuracy of a few micrometer. The alignment telescope can determine angle changes with a resolution of 5 arcsec.

In general the best focus position can be determined with a few micrometer accuracy using intra- and extra-focal measurements.

Depending on the setup and alignment requirements, it can be possible to use amplification effects to enhance misalignment effects, or differential measurements to cancel certain effects. It is also essential to choose stable references for the measurements.

IV. CRYOGENIC SPECTRAL MEASUREMENTS

A. Measurement Principles and Setup

The performance of optical coatings is generally tested on witness samples and not on the optical components themselves. For room temperature measurements the witness samples can be placed in the measurement compartment of the spectrometer. In order to measure the cryogenic spectral performance, a small cryostat has been designed to fit in the spectrometer measurement compartment: 'CRyostat in SPectrometer' (CRiSP). This cryostat has 2 sets of 2 windows to cover the entire wavelength range from UV to mid infrared wavelengths. The cryostat can hold 6 samples simultaneous for efficient use and rotates samples between the cryostat windows to be able to measure them in the spectrometer.

The Varian Fourier Transform Spectrograph FTS7000 has a resolution of 0,25 cm-1 @ 4000 cm-1 and a wavelength range from 200nm wavelength to 30 micrometer. It can be combined with the (CRiSP) facility for spectroscopic coating performance measurements under cryogenic conditions at temperatures down to 40K.

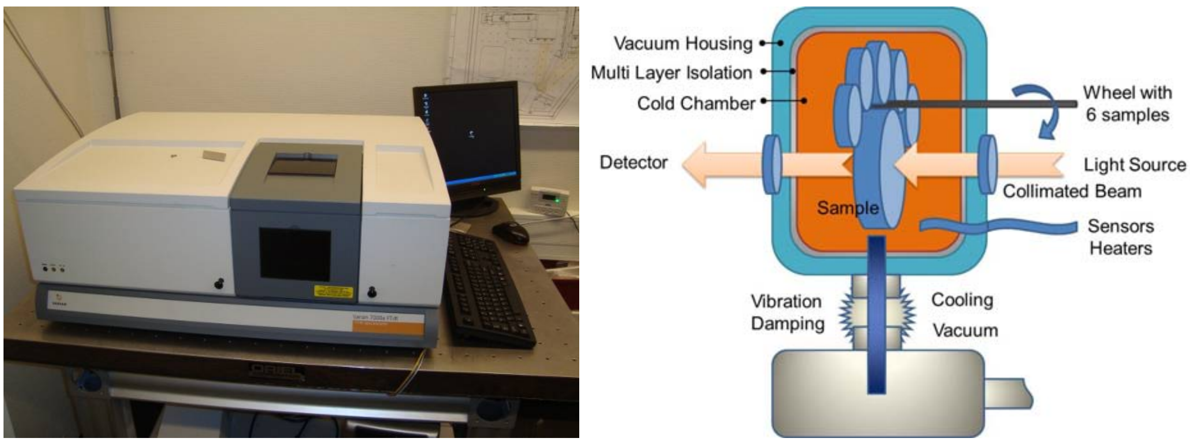


Fig. 5. Left: Varian FTS7000 Spectrometer. Right: Schematic overview of CRiSP measurement system.

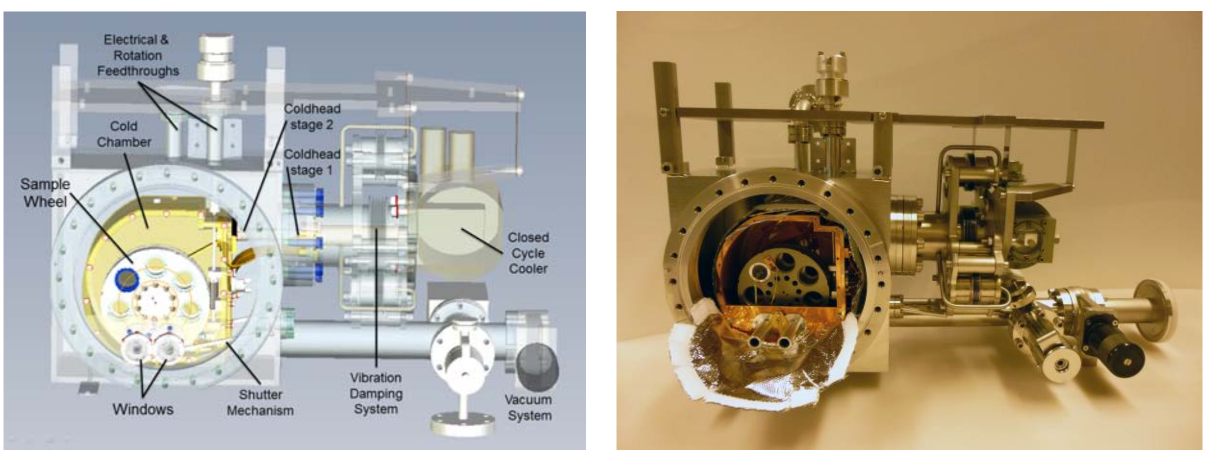


Fig. 6. Left: CRiSP design with the sample wheel on the left. Right: CRiSP hardware.

B. Error Contributions and Achieved Accuracies

The wavelength calibration of the spectrometer is linked to the HeNe laser wavelength interferometer and therefore very stable and accurate. The temperature of the samples can be determined with 0.1K accuracy. The angle of incidence is normal to within a degree.

The absolute transmission is the most difficult item to determine with high accuracy. One of the positions in the sample wheel must be an open position to act as a transmission reference. The stability of both the spectrometer illumination source and detector play a role. The absolute transmission is sensitive to variations in the alignment of the setup, e.g. a vignetted beam. Scattering and absorption can be different for the witness sample w.r.t. the actual optical component, because of surface roughness and (obvious) thickness differences. It is difficult to reach absolute transmission accuracies that are significantly better than 1%.

V. CRYOGENIC MATERIAL PROPERTIES MEASUREMENTS

Several techniques exist to measure the Index of Refraction (IoR). Most commonly used is the minimum deviation angle method. We chose to use Fabry-Pérot interferometry instead. Both methods are discussed.

A. Measurement Principles and Setup

Minimum deviation angle method: Any light beam passing through a prism will be refracted twice (Figure 7). The resultant deviation angle is dependent on the IoR. There exists a minimum deviation angle for each prism. This angle is dependent on the IoR (as a function of wavelength) and apex angle of the prism. Finding the minimum deviation angle and solving for the IoR has two great advantages over finding and solving the system for an arbitrary deviation angle. Working with the minimum deviation angle simplifies the geometry of the system and the dependence on initial incident angle is lost. The tolerance on the remaining apex angle also relaxes.

The Fabry-Pérot interferometry method uses fringing in a parallel plate to determine the IoR. Maxima in the transmitted spectrum occur if the wavelength fits an exact number of times in the parallel plate. The Optical Path Distance (OPD) is 2 * the thickness of the sample * the refractive index. Counterintuitively the OPD decreases if the angle of incidence is not normal. This is due to the extra path length needed outside the sample for wave fronts to combine and the larger angles outside the sample (Figure 7).

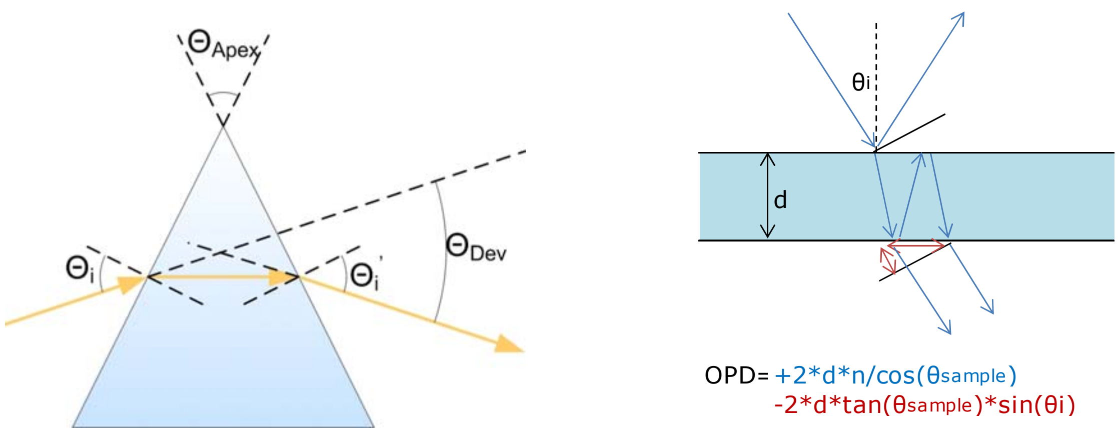


Fig. 7. Left: Schematic overview of the minimum deviation refractometry method to determine the index of refraction. Right: Schematic overview of the Fabry-Pérot fringing method to determine the index of refraction.

The minimum deviation method uses discrete wavelengths, while Fabry-Pérot interferometry method can cover a wide wavelength range in a single measurement. The minimum deviation method requires moving parts very accurately in the cryogenic environment, which is always a burden. The Fabry-Pérot interferometry method requires accurate knowledge of the Coefficient of Thermal Expansion (CTE), but this information is required anyhow in order to determine lens curvatures at the operating temperature and design proper lens mounts for cryogenic environments.

The Varian FTS7000 and CRiSP are used for the Fabry-Pérot measurements (see section IV). A peak finding algorithm in MATLAB determines the wavelength of each interference maximum. Literature values can be used to determine the exact order number of the fringes. Alternatively samples of different thickness can be used to determine the exact order number; the slope of the IoR over the spectrum will not match for incorrect order numbers. Thin samples are more sensitive to the order number, while thick samples give more accurate results.

The thickness of the sample is measured at room temperature with a calibrated linear displacement gauge (LVDT). A CTE measurement setup counts interferometric laser fringes while the temperature of the sample is varied over time from room temperature to operating temperature (figure 8).

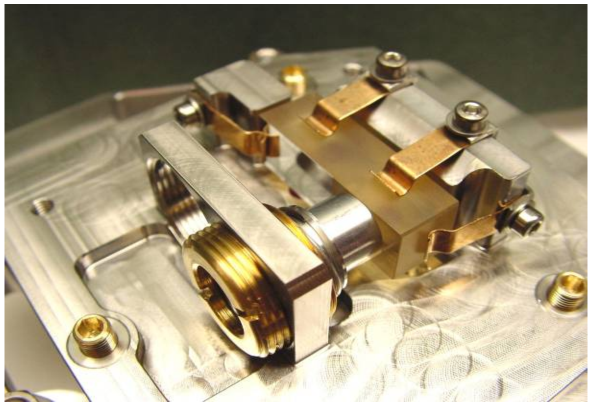


Fig. 8. Cryogenic vacuum CTE measurement setup

B. Error Contributions and Achieved Accuracies

Error analyses are shown for both the minimum deviation angle method and the Fabry-Pérot interferometry method, in order to get an impression of how stringent the constraints are on the variables that influence the IoR.

Minimum deviation angle: All statistical errors in the angles are assumed to be random. Systematic errors are not considered is this analysis. There are two main sources of uncertainty, the minimum deviation angle and the apex angle. In order to achieve accuracies of 10^{-5} or higher, the errors in the angle determinations have to be as good or better. A very detailed error analysis for the minimum deviation method is given in [3]. It states that precision measurements (accuracy 10^{-5}) require the errors in the angles to be less than 0.2 arcsec and prism surface flatness of λ/20 or better.

Table 2. Sources of uncertainty in the minimum deviation method and their maximum values.

	Maximum errors permissible at relative uncertainty given		
relative uncertainty	10^{-4}	10^{-5}	10^{-6}
apex angle [deg]	2’’	0.2’’	0.02’’
Min Dev angle [deg]	2’’	0.2’’	0.02’’
Intrinsic birefringence	10^{-4}	10^{-5}	10^{-6}
lack of flatness [deg]	0.4’’	0.04’’	0.004’’
pyramidal error [deg]	2’’	0.2’’	0.02’’
temperature [K]	1	0.1	0.01

The formula for Fabry-Pérot interferometry depends on the fringe order *m*, the wavelength λ_m and the sample Optical Path Distance (OPD) as written in figure 7:

$$n(\lambda_m) = \frac{m \cdot \lambda_m}{2 \cdot OPD} \tag{4}$$

Potential sources of error are: sample thickness, fringe maxima locations, incident angle and temperature. These are all expected to be random. The fringe order must be known exactly. The relative uncertainty estimate shows that these error sources have a one-on-one relation for the thickness and fringe maxima locations.

Table 3. Sources of uncertainty in the Fabry-Pérot interferometry method and their maximum values.

	Maximum errors permissible at relative uncertainty given		
relative uncertainty	10^{-4}	10^{-5}	10^{-6}
fringe order	0	0	0
incident angle [deg]	0.1	0.03	0.01
intrinsic birefringence	10^{-4}	10^{-5}	10^{-6}
plane parallel-ness [deg]	0.1*n	0.03*n	0.01*n
Thickness	10^{-4}	10^{-5}	10^{-6}
Spectral resolution [cm^{-1}]	$4*10^{-2}$	$4*10^{-3}$	$4*10^{-4}$
Temperature [K]	0.5	$5*10^{-2}$	$5*10^{-3}$

The angle of incidence must be known accurately, but this does not mean that the sample has to be aligned this accurate. It is possible to calibrate the angle of incidence using multiple measurements at different angle of incidence e.g. at -1, 0 and +1 degrees, resulting in an angle calibration accuracy of 0.03 degrees.

The Spectral Resolution in our setup is 400 at 25μm, 4000 at 2.5μm and 40000 at 250nm.

Accurate thickness measurements proved to be difficult. Only after recalibrating the LVDT an absolute thickness accuracy of 2mm ± 80nm could be achieved = $4 \cdot 10^{-5}$. A wedge in the sample and surface flatness of both sides of the sample have been taken into account in this value. CTE measurements have a typical value of $X \cdot 10^{-5}$ and an accuracy of $\sim 10^{-5}$. We consider optical contacting in combination with interferometric measurements as a way to improve the thickness and CTE measurements.

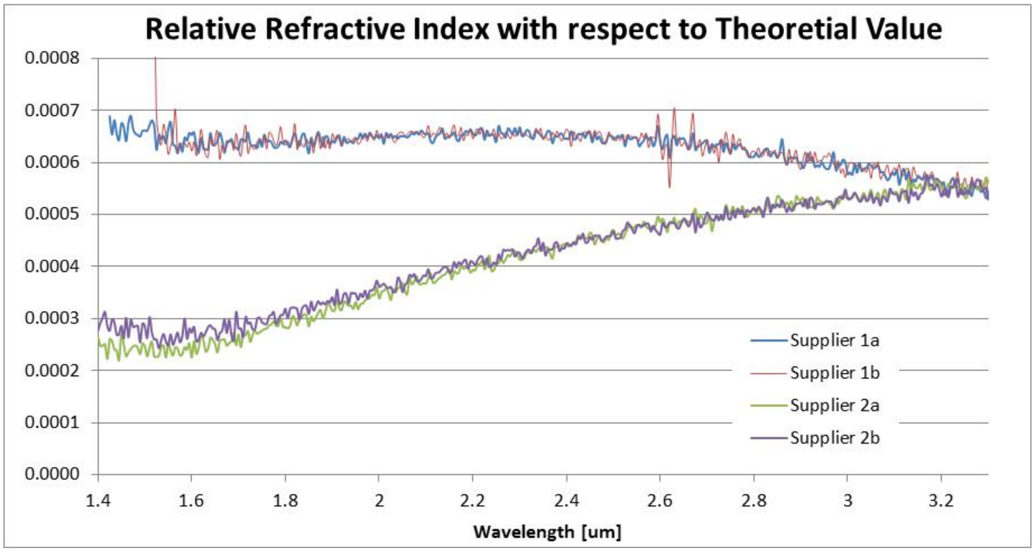


Fig. 9. Repeatability of refractive index measurements (measurements a & b). The refractive index of a high purity single crystal material is measurably different for different material suppliers.

In the current setup the index of refraction of optical and infrared materials can be measured with an absolute accuracy better than $2 \cdot 10^{-4}$ using Fabry Perot fringing. Measurement repeatability over multiple samples of different materials indicate that the achieved relative accuracy is better than $2 \cdot 10^{-5}$.

VI. CONCLUSION AND SUMMARY

It is not trivial to measure opto-mechanical properties of optical components, coatings and complete optical systems to the level required for state of the art equipment, especially under cryogenic conditions. Several methods have been developed and presented in this paper, including their measurement accuracies.

In summary the capabilities are: Interferometric wave front error measurements of components up to 150mm diameter and temperatures down to 20K, with accuracies of 11nm RMS. Spectroscopic coating performance measurements under cryogenic conditions using the CRiSP facility, with wavelengths ranging from 200nm to 30micrometer and temperatures from 40K to 300K and an absolute transmission accuracy better than 1%. The CTE can be determined with an accuracy of $\sim 10^{-5}$ and the index of refraction of optical and infrared materials can be measured with an absolute accuracy better than $2 \cdot 10^{-4}$ using Fabry Perot fringing. The performance of cryogenic optical systems with a diameter up to half a meter can be verified down to 12K. An adjustable gravity orientation system can position an optical bench (in a cryostat) in any orientation with respect to the gravity.

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